CUORICINO: final results

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University and INFN - Genova

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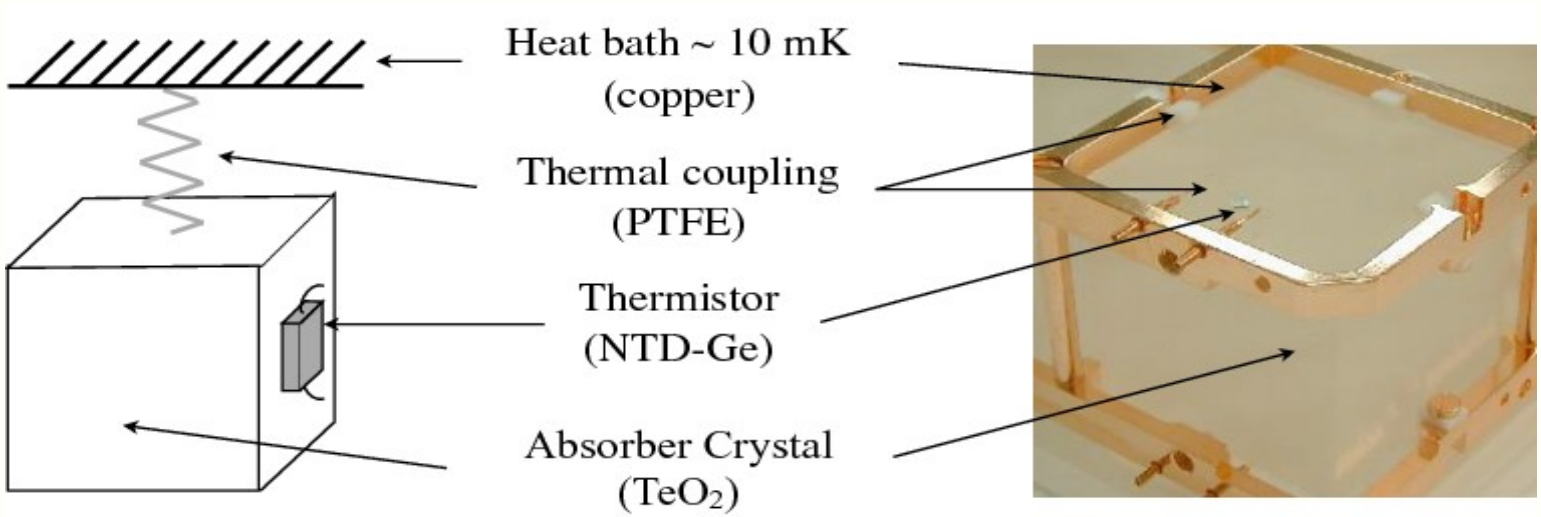
Outline

CUORICINO was a bolometric experiment for the search of neutrinoless double beta decay (DBD) in ^{130}Te

- Detector description
- Results for ^{130}Te neutrinoless DBD to the ground state
- Results for ^{130}Te DBD to the first excited state 0^+ of ^{130}Xe
- Results for β^+/EC DBD of ^{120}Te
- Study of the muon-induced background in CUORICINO
- Feasibility of WIMP and solar Axion search in CUORE-0 and CUORE

Bolometric technique

Working principle: measure the temperature rise of the energy absorber $\Delta T = \frac{E}{C}$



source ≡ detector

Typical parameters of the CUORICINO bolometers

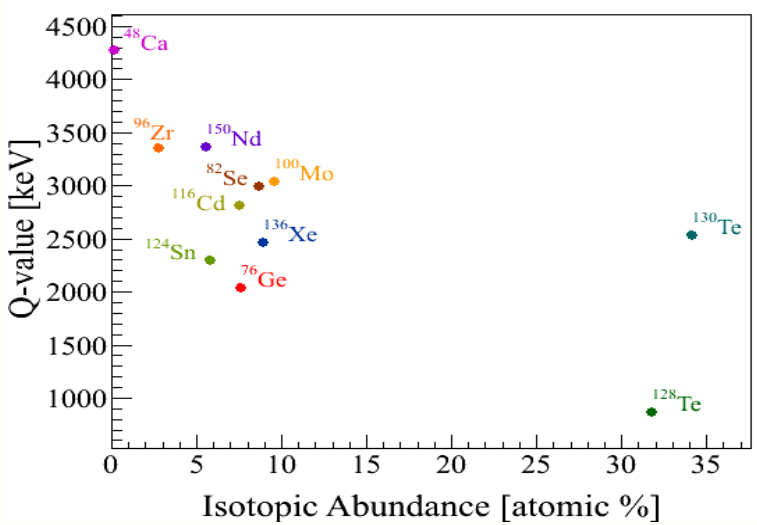
Absorber crystal: TeO_2

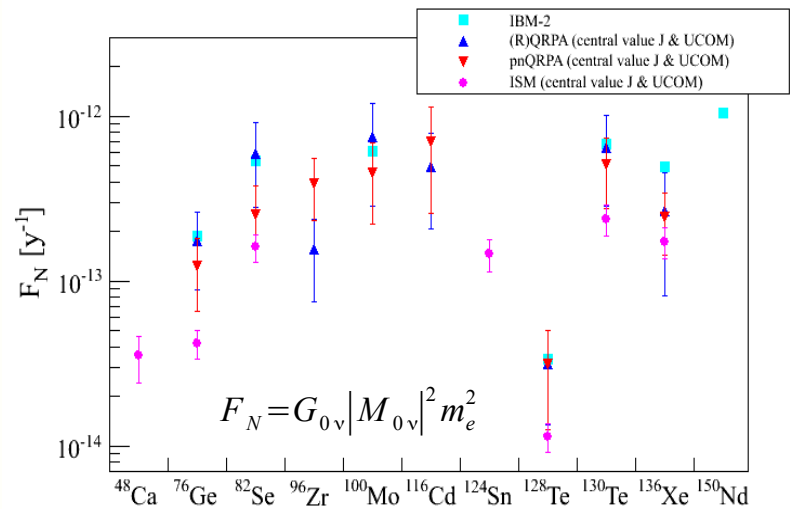
- M = 790 g
- C = 2 x 10^{-9} J/K
- ΔT = 0.1 mK/MeV

Sensor: NTD Ge thermistor

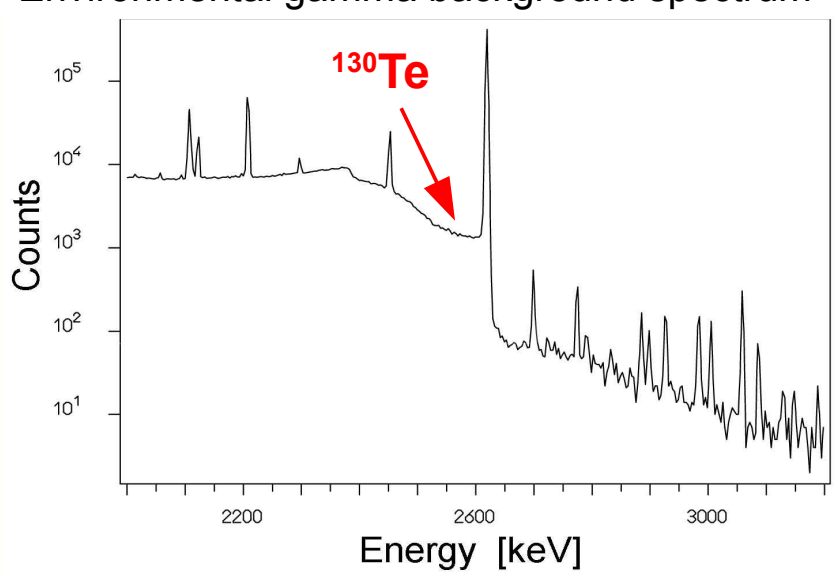
- $R = R_0 \exp\left(\frac{T_0}{T}\right)^{1/2}$
- R_0 = 1 Ω, T_0 = 3 - 4 K
- R = 100 MΩ
- ΔR = 3 MΩ/MeV, ΔV = 0.3 mV/MeV

Isotope choice: ^{130}Te





Environmental gamma background spectrum



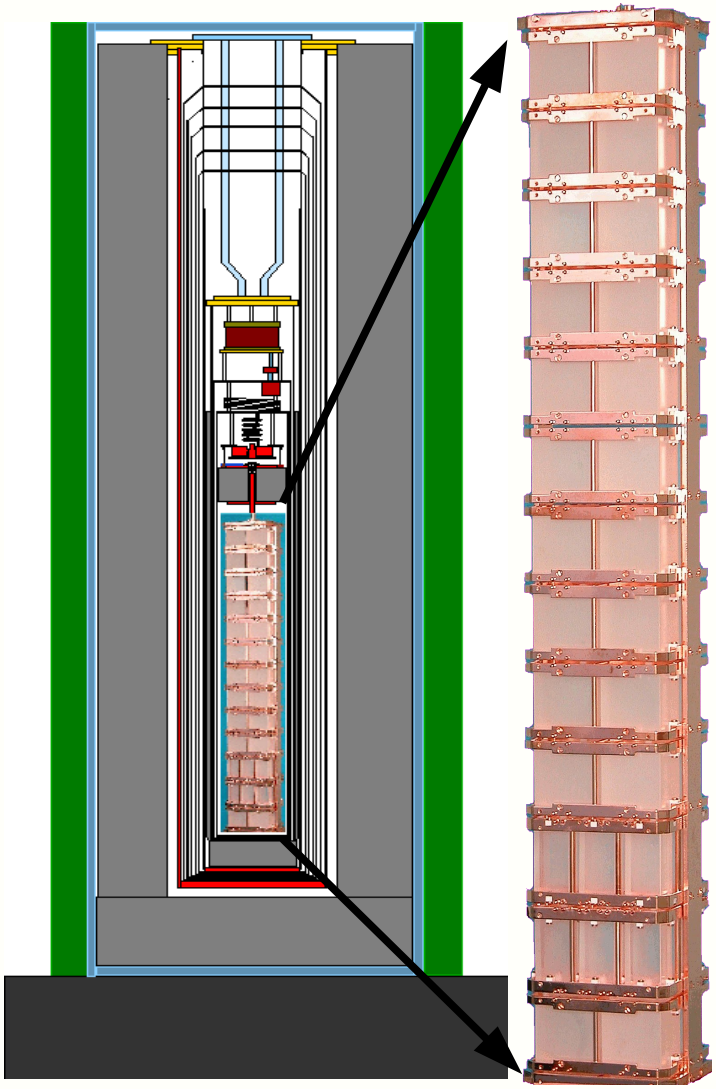
- Q-value: ~2527.5 keV
- Isotopic abundance: 33.8%
- Favorable nuclear structure factor
- TeO_2 crystals have good thermal and mechanical properties

Q-value measurements:

2527.518(13) keV	*Phys. Rev. Lett. 102, 212502 (2009)*
2527.01(32) keV	*Phys. Rev. C 80, 025501 (2009)*
2526.97(23) keV	*Rahaman et al., Phys. Lett. B (2011),* **in press**

Detector

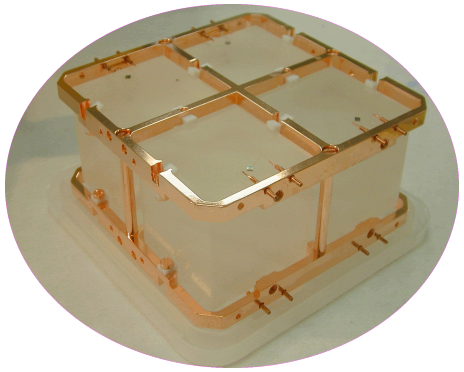
Detector maintained at ~10 mK by a $^3He/^4He$ dilution refrigerator

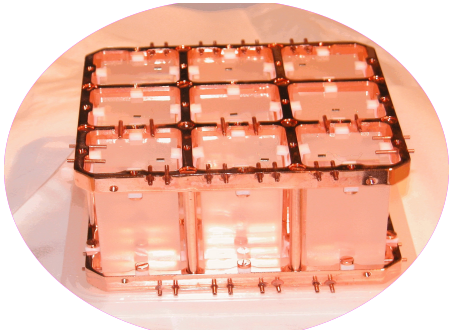


A tower of 62 TeO_2 crystals

11 floors made of 4 crystals
- not enriched
- Mass: 790g
- Dimensions: 5x5x5 cm^3

2 floors made of 9 crystals:
- Mass: 330g
- Dimensions: 3x3x6 cm^3
- 2 enriched in ^{128}Te (82%)
- 2 enriched in ^{130}Te (75%)





Total mass: 40.7 Kg (11.3 Kg in ^{130}Te)

Shieldings

Internal:

➔1cm low activity Pb
(A < 4 mBq/Kg in ^{210}Pb)

External:

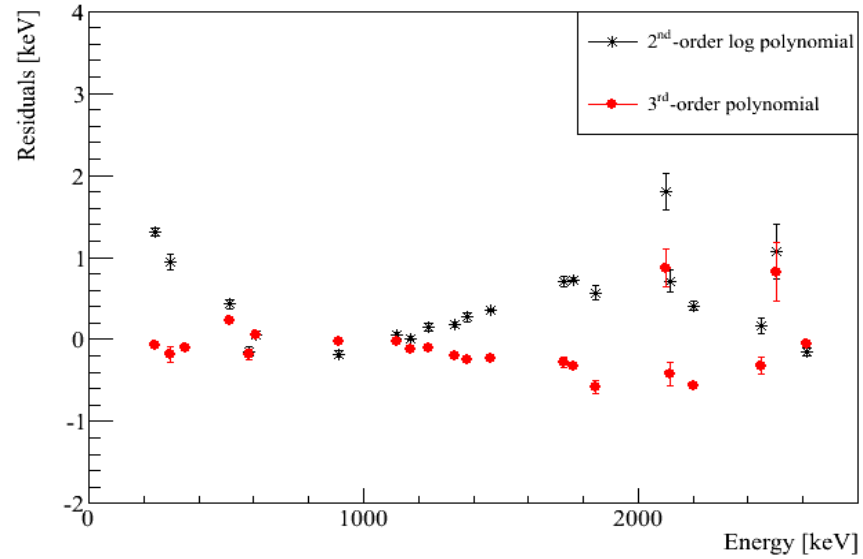
➔20cm Pb
➔20cm Borated Polyethylene
➔Anti-Rn box: Nitrogen overpressure

Energy calibration

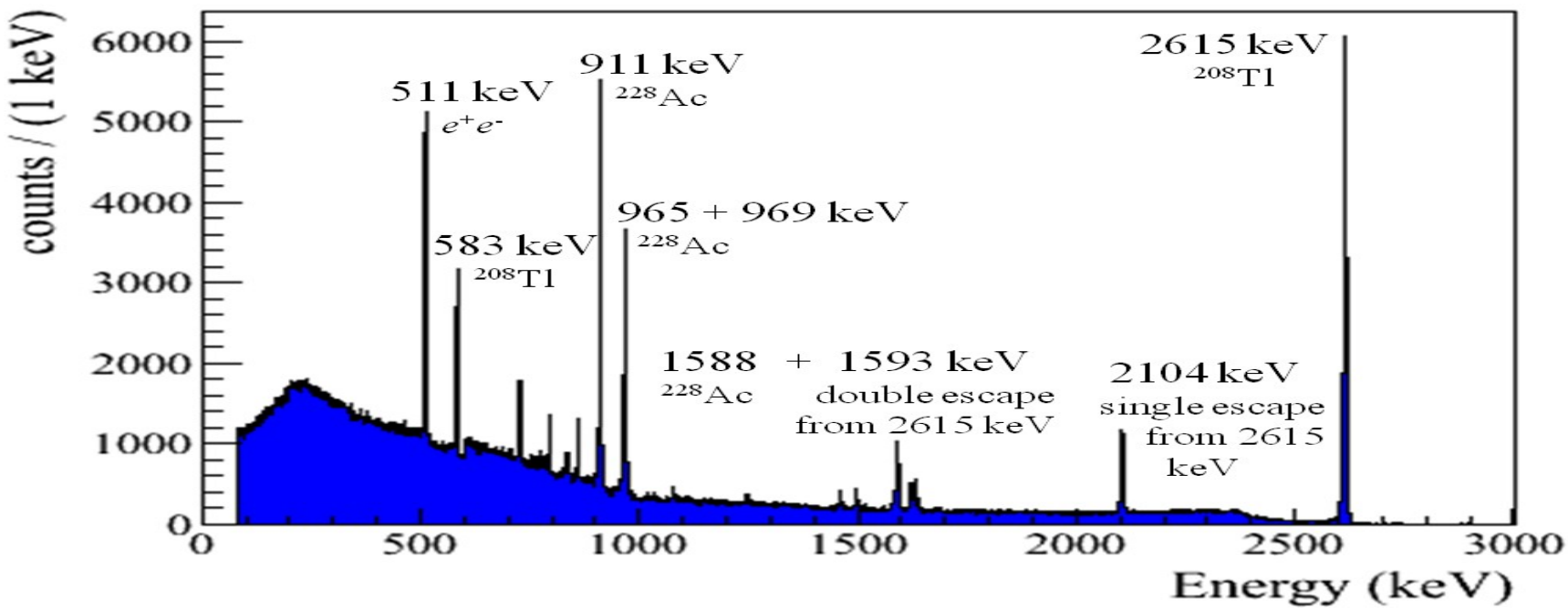
~3 days calibration performed about once per month by inserting ^{232}Th sources between the cryostat and the external lead shields

Calibration error at ^{130}Te ββ Q-value: **± 0.4 keV**

Energy residuals for 2 different calibration functions

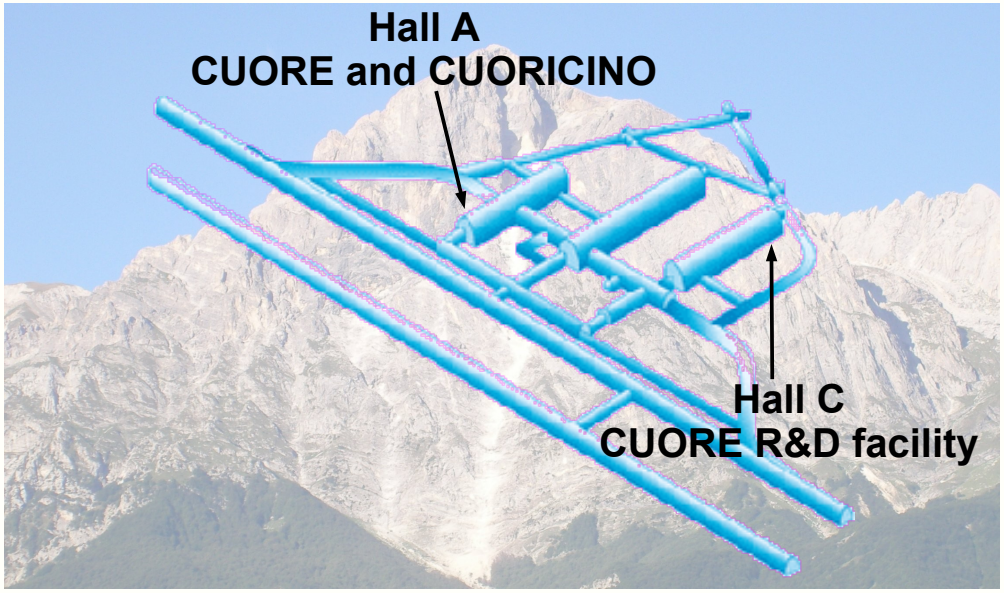


Calibration spectrum

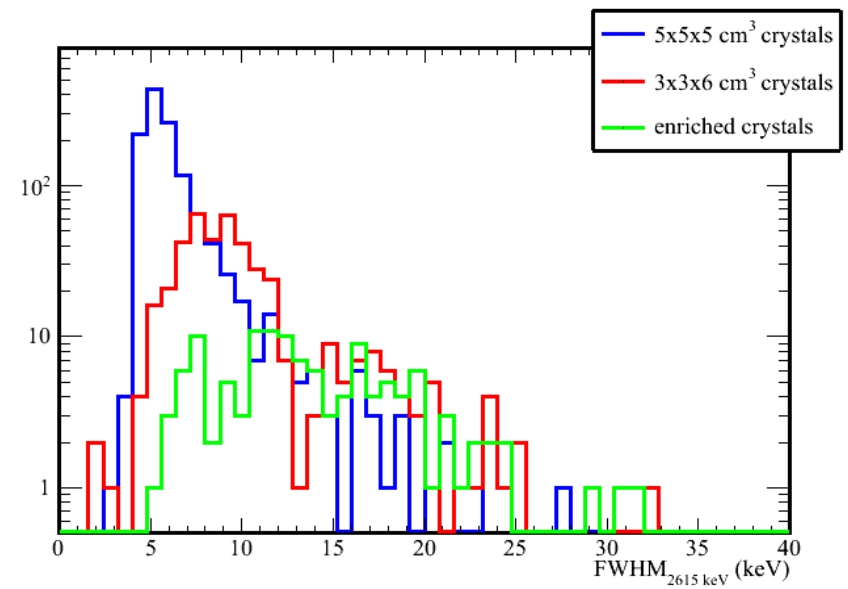


Operation and performances

Cuoricino was located underground, in the Hall A of the Laboratori Nazionali del Gran Sasso (Italy) under a 3650 m w.e. shield against cosmic rays



Average energy resolution (big xtals): **6.3 keV**
Evaluated on the 2615 keV peak from ^{208}Tl



Data taking started in April 2003 and ended in June 2008. The data are separated in two runs (RUN I and RUN II), due to a major maintenance interruption

Crystal Type	$< \Delta E_{FWHM} >$
$5 \times 5 \times 5$ cm^3	6.3±2.5 keV
$3 \times 3 \times 6$ cm^3 (natural)	9.9±4.2 keV
$3 \times 3 \times 6$ cm^3 (enriched)	13.9±5.3 keV

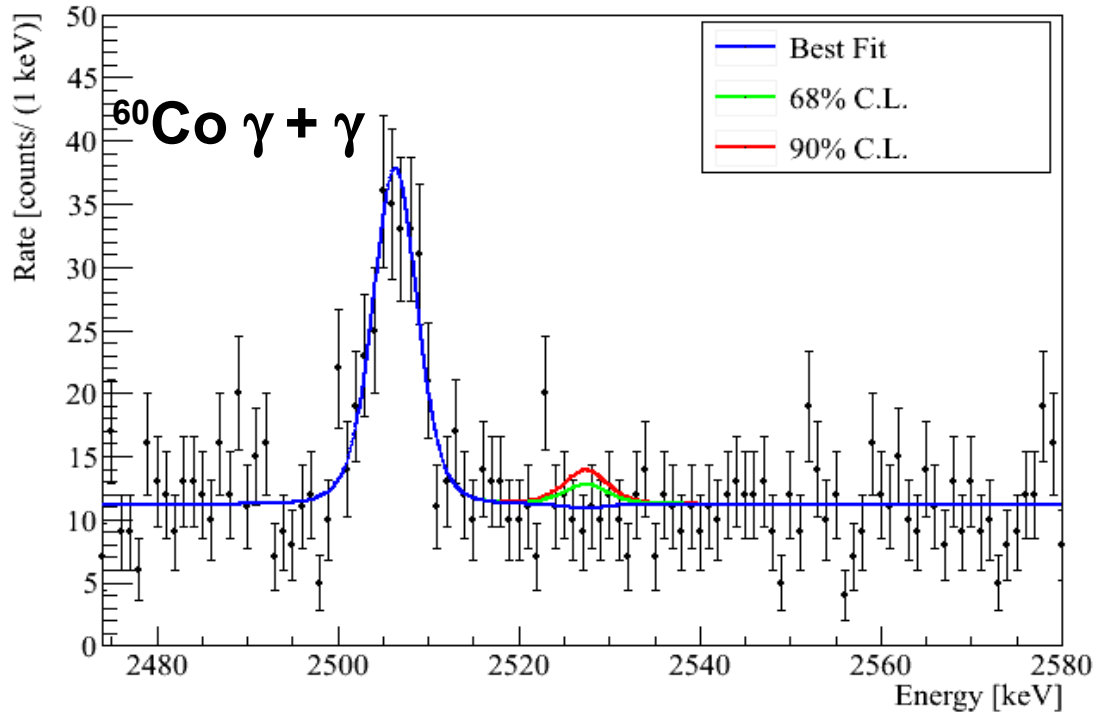
^{130}Te ββ0ν decay to the ground state

Bkg at Q-value: **0.17 counts/(keV kg y)**

Statistics: **19.75 kg(^{130}Te) y**

Maximum likelihood fit with 8 free parameters:
- 0νββ rate
- 3 flat bkg rates (big, small and enriched xtals)
- 3 ^{60}Co rates (big, small and enriched xtals)
- ^{60}Co sum energy (same for all detectors)

$$\Gamma^{0\nu} = (-0.2 \pm 1.4(stat) \pm 0.3(syst)) \times 10^{-25}\, y^{-1}$$



Half life limit: Bayesian approach with flat prior

$$T^{0\nu}_{1/2} > 2.8 \times 10^{24}\, y \quad @\, 90\%\, CL$$

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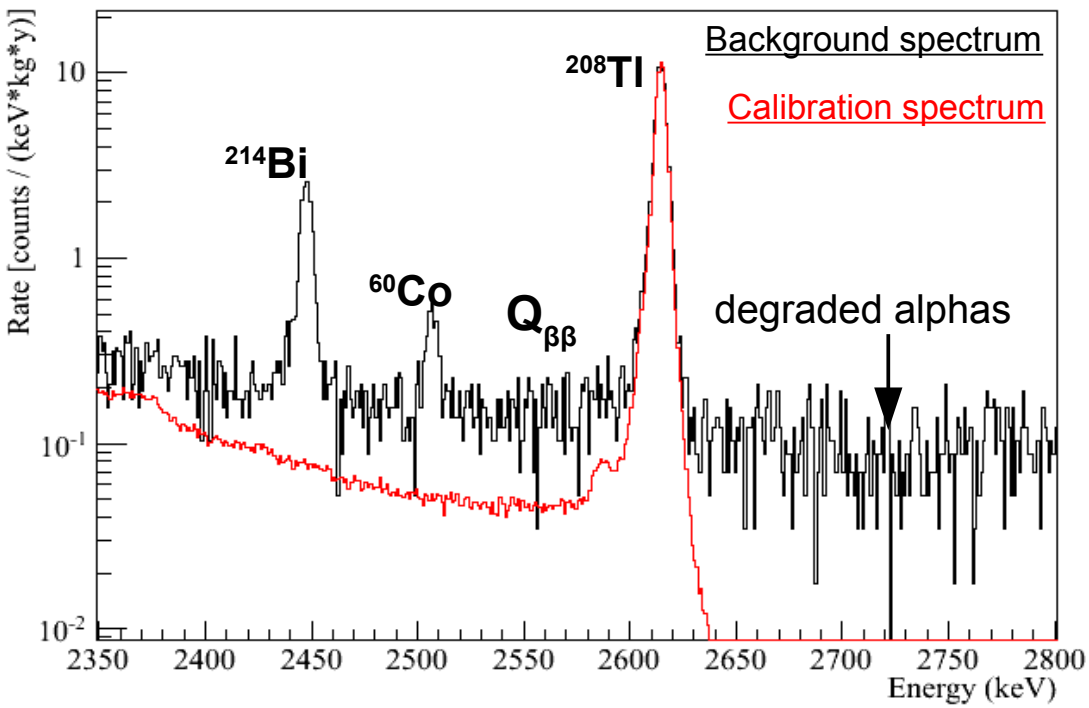
The CUORICINO limit on $m_{\beta\beta}$ is comparable with the one reported by the Heidelberg-Moscow experiment in ^{76}Ge, but can not exclude the claim of observation

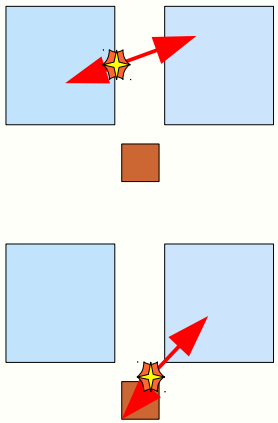
$m_{\beta\beta}$	< (300 – 570) meV	(R)QRPA	*Phys. Rev. C 77, 045503 (2008)*
	< (360 – 580) meV	pnQRPA	*J. Phys. Conf. Ser. 173, 012012 (2009)*
	< (570 – 710) meV	ISM	*Nucl. Phys. A 818, 139-151 (2009)*
	< 370 meV	IBM-2	*Phys. Rev. C 79, 044301 (2009)*

CUORICINO background



Surface alpha contaminations produce a continuous spectrum that extends down to the $Q_{\beta\beta}$ region

The contributions of copper and crystal contaminations can be studied by comparing the single and double hit energy spectra



Crystal contamination: double hit

Copper contamination: single hit

Background contributions at $Q_{\beta\beta}$

- ^{60}Co from cosmogenic activation: negligible
- Multi-Compton from ^{208}Tl (^{232}Th cont. in cryostat shields): ~40%
- Degraded alphas from crystal surfaces: ~10%
- Degraded alphas from Cu holders surfaces: ~50%
- Muon-induced background: negligible

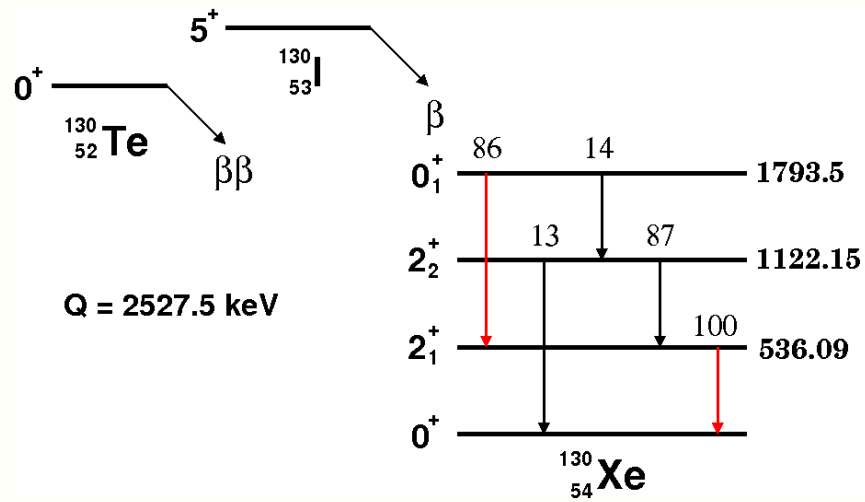
Tests performed in the Hall C R&D facility showed that the alpha background can be reduced by proper cleaning procedures.
The crystal surface contribution is now under control, while the copper surface contribution is still a factor of 4 above the CUORE background goal (10^{-2} counts/(keV kg y))

More on P. Gorla's talk

^{130}Te DBD to the excited state 0^+ of ^{130}Xe

Decay accompanied by the emission of two γ's:
1257 keV and **536 keV**

The electrons (and neutrinos, in the 2ν decay mode) share a total energy of 734 keV



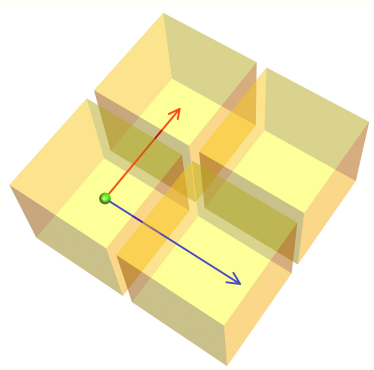
Theoretical calculations:

0ν ($m_{\beta\beta}$ = 1 eV): $T^{0\nu}_{1/2} = 7.5 \times 10^{25}\ y$

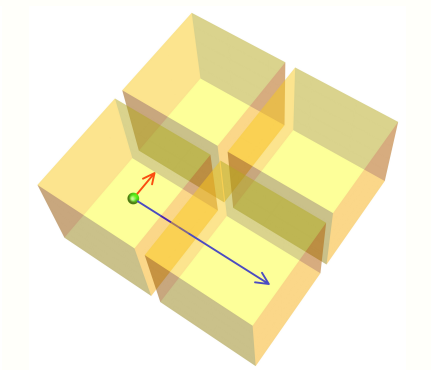
2ν: $T^{2\nu}_{1/2} = (0.5 \div 1.4) \times 10^{23}\ y$

Coincidence-based analysis

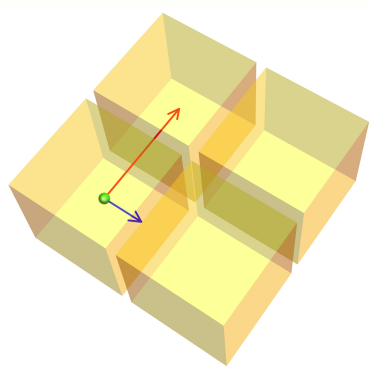
- Search for events involving two or three crystals
- Require that the photons are completely absorbed in one crystal
- Three possible scenarios:



Both γ's escape the decay crystal



The 1257 keV γ escapes. The 536 keV γ is trapped in the decay crystal

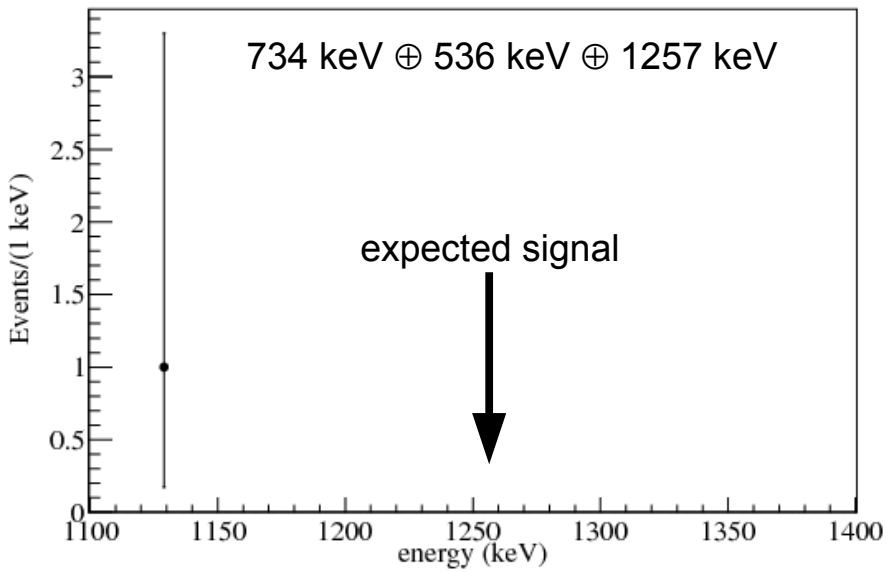


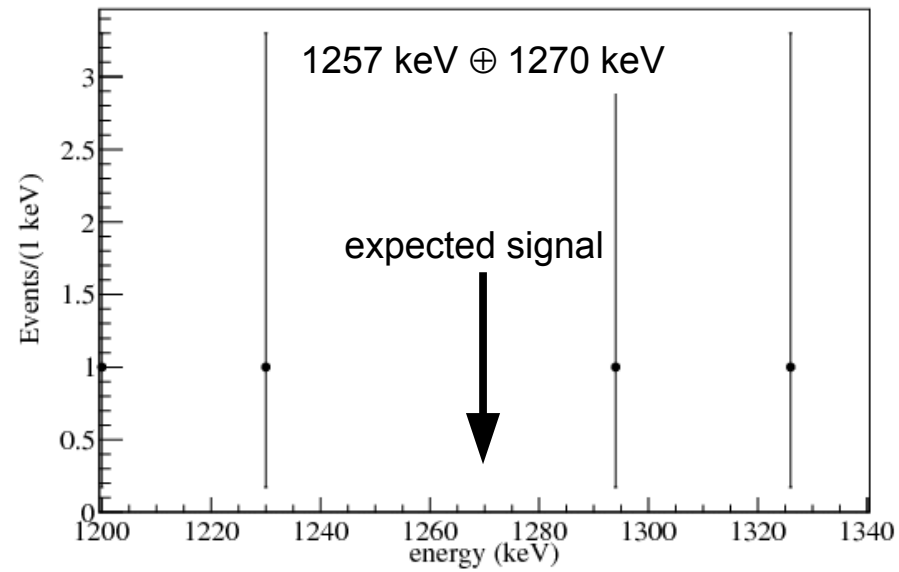
The 536 keV γ escapes. The 1257 keV γ is trapped in the decay crystal

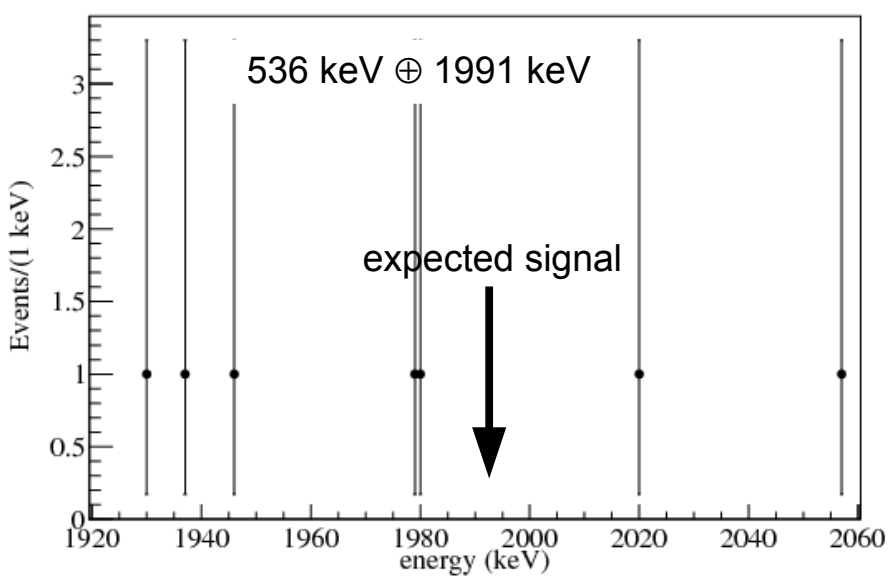
Signature [keV]	Decay	Efficiency [%]
734 ⊕ 536 ⊕ 1257	0ν	0.44 ± 0.02
1257 ⊕ 1270	0ν	1.79 ± 0.04
536 ⊕ 1991	0ν	1.10 ± 0.03
(0 – 734) ⊕ 536 ⊕ 1257	2ν	0.41 ± 0.02
(536 – 1270) ⊕ 1257	2ν	2.29 ± 0.05
(1257 – 1991) ⊕ 536	2ν	1.00 ± 0.03

Signal search is performed on the hit highlighted in red in the above table

Excited states: 0νDBD







No evidence for a signal, background negligible

Use poisson posterior p.d.f. for zero observed events

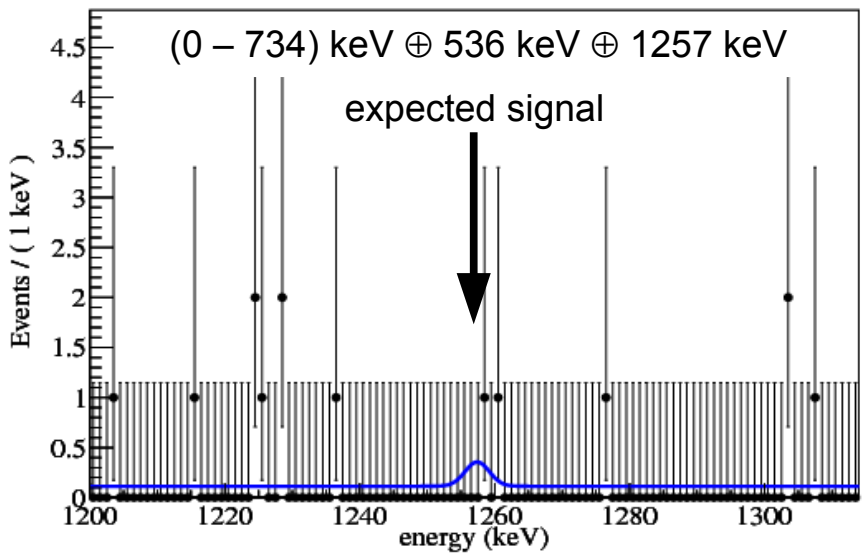
Half life limit extracted with a Bayesian approach, assuming a flat prior

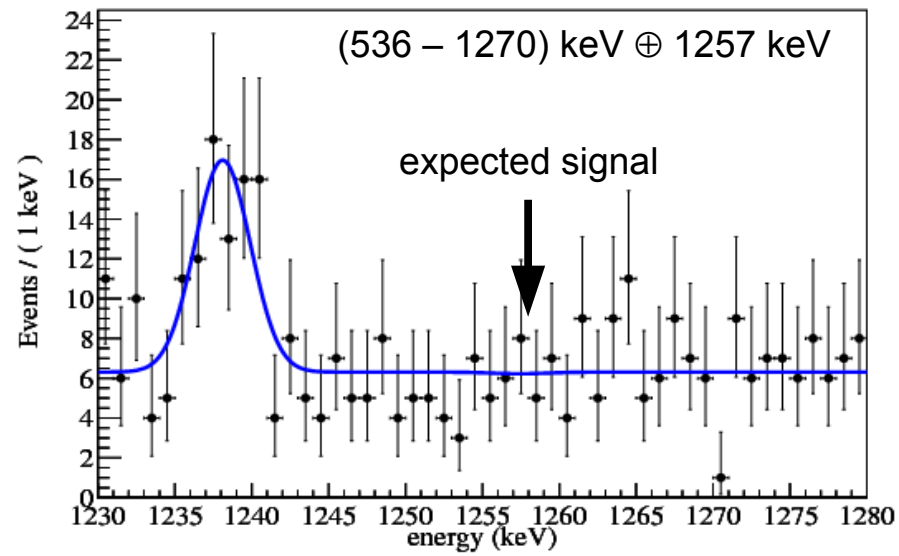
$$T^{0\nu}_{1/2}\left({}^{130}Te \rightarrow {}^{130}Xe^{*}\right) > 9.4\times10^{23}\,y \quad @\,90\,\%\,CL$$

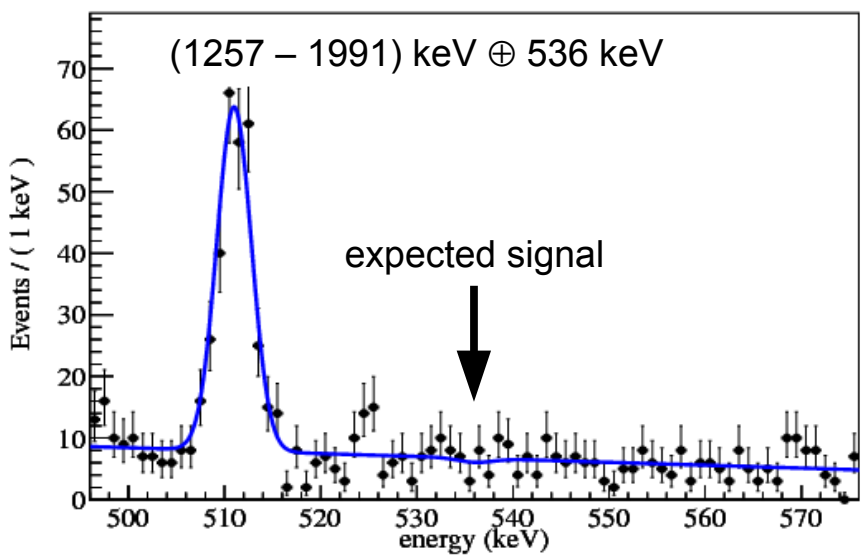
Limit improved by almost two orders of magnitude with respect to previous publications

arXiv:1108.4313

Excited states: 2νDBD







Signal search performed using a ML unbinned fit

Half life limit extracted with a bayesian approach, assuming a flat prior

$$T_{1/2}^{2\nu}\left({}^{130}Te \rightarrow {}^{130}Xe^{*}\right) > 1.3\times10^{23}\,y \quad @\,90\%\,CL$$

Limit improved by almost two orders of magnitude with respect to previous publications

arXiv:1108.4313

^{120}Te β^+/EC double beta decay

$$^{120}Te \rightarrow {}^{120}Sn + e^+ (+2\nu)$$

Q = (1714.8 ± 1.3) keV

Theoretical calculations:

0ν: not available
2ν: $T_{1/2}^{2\nu} = 4.4 \times 10^{26}\ y$

Isotopic abundance: **0.096%**

Statistics: **0.0573 kg(^{120}Te) y**

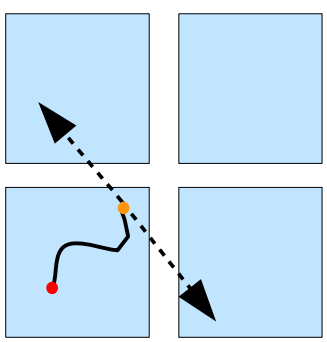
Analysis approach

binding energy of the captured electron

In the 0ν decay mode, the energy transferred to the positron is $K_{max} = Q - 2\ m_e c^2 - E_b$
If E_b is contained in the detector, the total energy release is $E_0 = K_{max} + E_b = 692.8$ keV

In the 2ν decay mode the kinetic energy of the positron has a continuous distribution between E_b and K_{max} (E_b = 30.5 keV if the capture proceeds through the K shell)

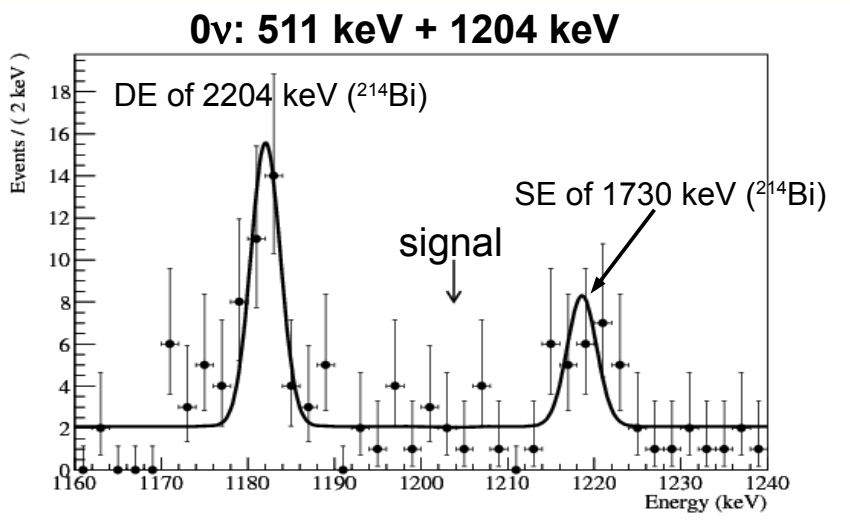
Coincidence-based analysis: search for events in coincidence with one or two 511 keV gammas (from positron annihilation)

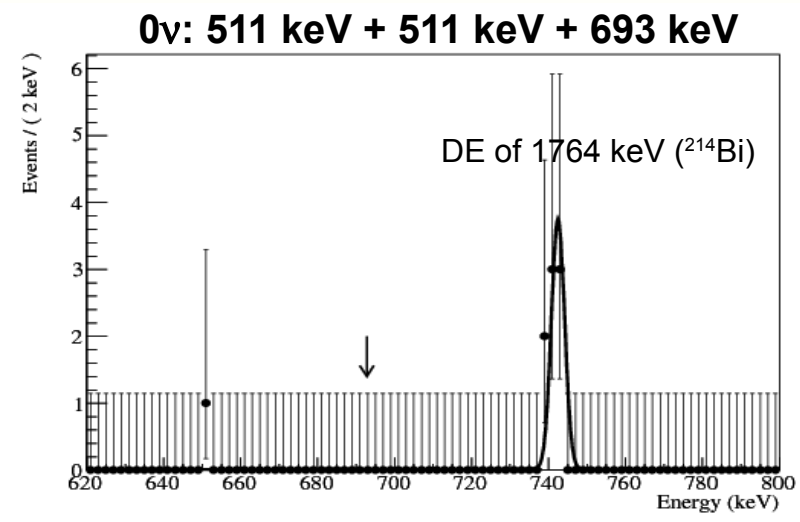


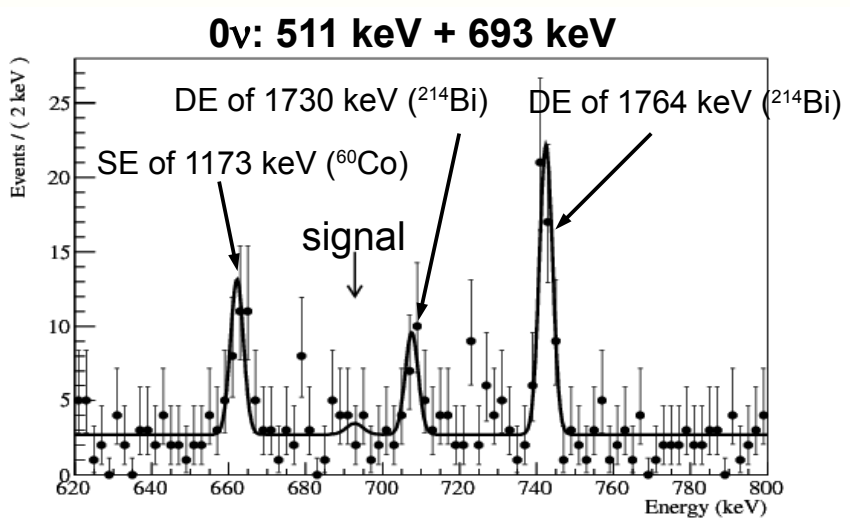
0ν	2ν	Efficiency
692.8 keV ⊕ 511 keV	(30.5 - 692.8) keV ⊕ 511 keV	3.40 ± 0.02 %
692.8 keV ⊕ 511 keV ⊕ 511 keV	(30.5 - 692.8) keV ⊕ 511 keV ⊕ 511 keV	0.45 ± 0.01 %
1203.8 keV ⊕ 511 keV	(541.5 - 1203.8 keV) ⊕ 511 keV	6.23 ± 0.03 %

Efficiencies evaluated using a GEANT4-based simulation

^{120}Te β^+/EC: 0νDBD







Global upper limit for the number of signal counts obtained by combining the posterior p.d.f.s of the three considered signatures

$$T^{0\nu}_{1/2} > 1.9 \times 10^{21}\, y \quad @90\%\, CL$$

Limit improved by more than four orders of magnitude with respect to previous publications

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^{120}Te β^+/EC: 2νDBD

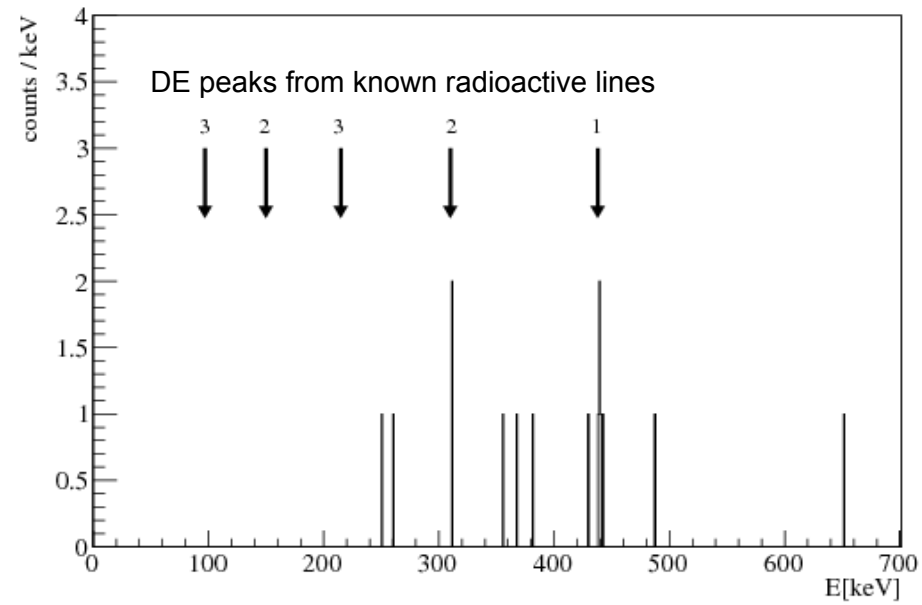
For the 2ν analysis consider only the signature with the best signal to background ratio:
(30.5 – 693) keV ⊕ 511 keV ⊕ 511 keV

Background sources

Physical coincidences: remove events within ±3σ around the DE peaks from known radioactive lines:

- 1120.3 keV and 1238.1 keV of ^{214}Bi (3)
- 1173.2 keV and 1332.5 keV of ^{60}Co (2)
- 1460.8 keV of ^{40}K (1) ⇨ **8 events left**

Random coincidences: estimated looking at the spectra of events in triple coincidence with the side bands of the 511 keV peak: **4.3 events**



upper limit on the number of signal counts estimated using a Bayesian approach
Assume 4 bkg events over 8 observed events:
n_{SIG} < 9 @ 90% CL

$$T^{2\nu}_{1/2} > 0.9 \times 10^{20}\, y \quad @90\%\, CL$$

Limit improved by almost three orders of magnitude with respect to previous publications

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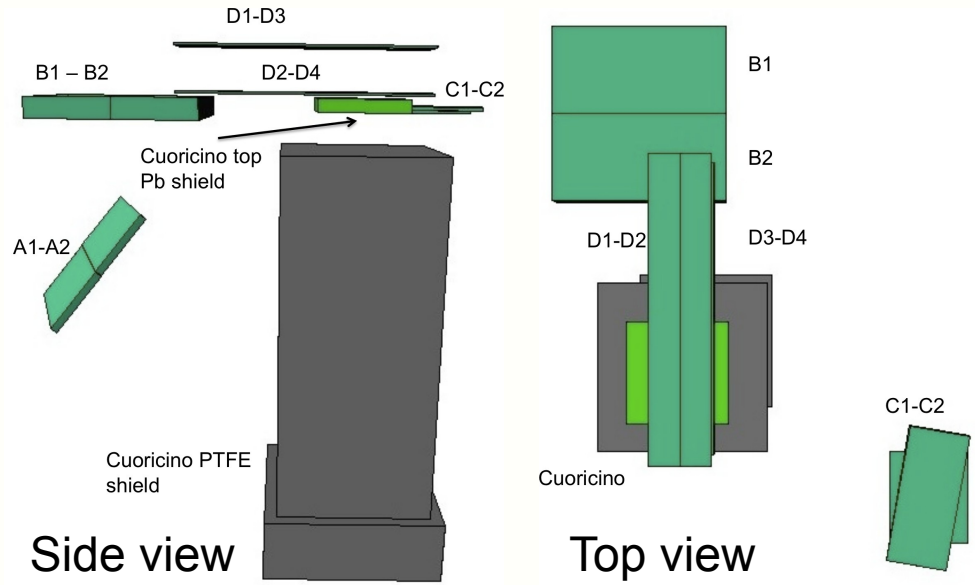
Muon-induced background

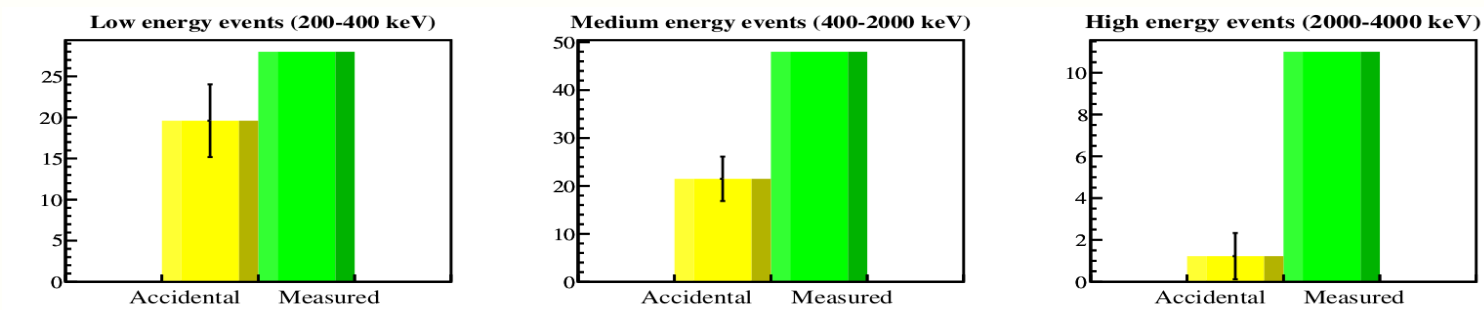
A test with plastic scintillators surrounding the CUORICINO detector was performed in the last 3 months of data taking of the experiment

Study the correlations between the bolometric signals and the triggers from the plastic scintillators

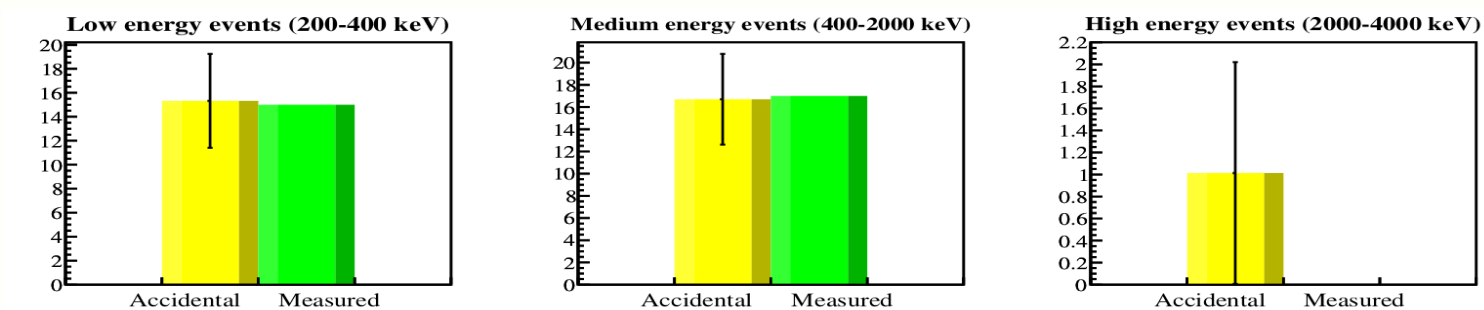
The test showed that operating the bolometers in anti-coincidence is effective at eliminating potential muon-induced backgrounds



Before anti-coincidence cuts



After anti-coincidence cuts



BKG_{μ} at 2530 keV < 0.0021 counts / (keV kg y) @ 95% CL

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Low energy threshold trigger

New trigger algorithm: energy threshold down to few keV

Key concept: run the trigger on data processed with the optimum filter. Higher SNR ⇒ lower threshold

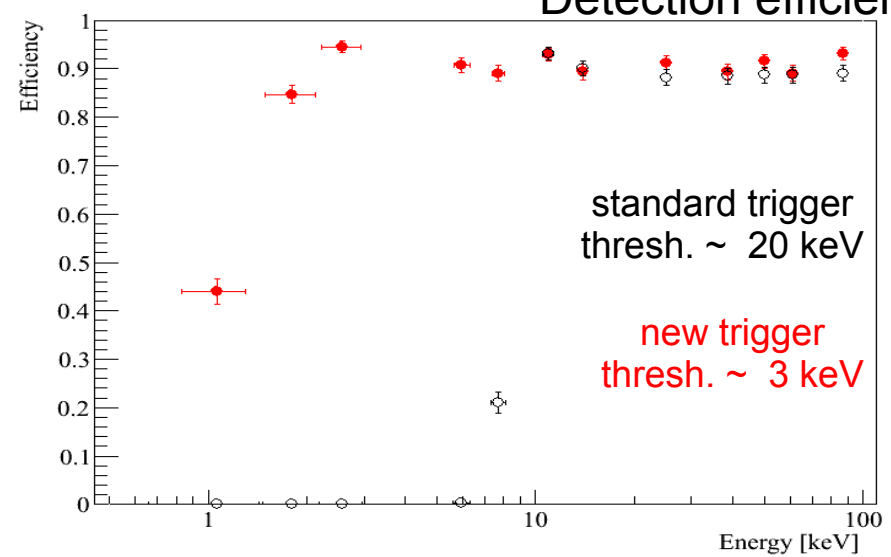
$$H(\omega) = \frac{S^*(\omega)}{N(\omega)} e^{-i\omega t_m}$$

average signal shape (estimated from data)

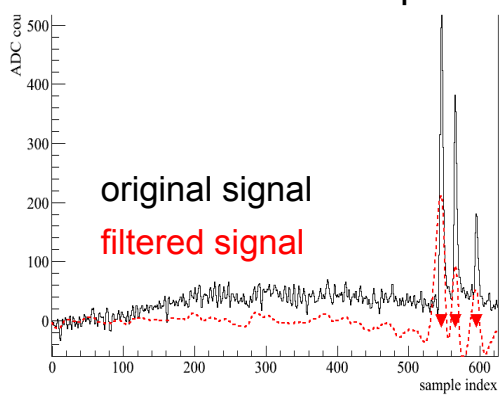
maximum position

noise power spectrum (estimated from data)

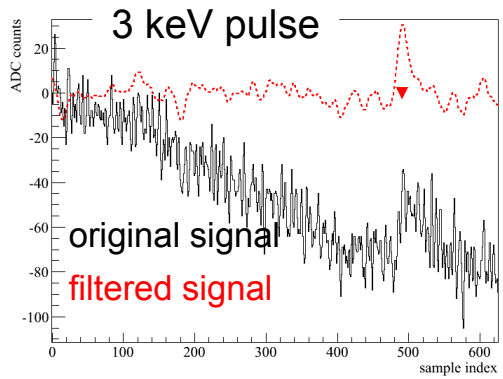
Detection efficiency

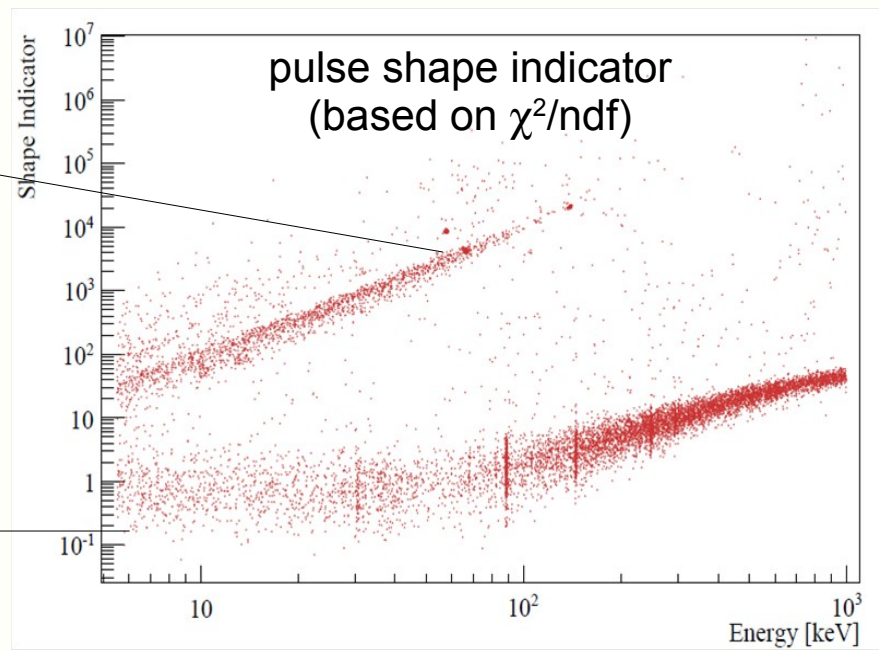


electronics-induced spikes



3 keV pulse





Study performed on three test bolometers

The region of interest for WIMP and Axion interactions in TeO_2 is **below 25 keV**

The new trigger algorithm, with a threshold of few keV, opens the possibility to search for dark matter signals in CUORE-0 and CUORE

JINST 6 (2011) P02007

Conclusions

- CUORICINO set the most sensitive limits on the half life of the following processes:
  - ^{130}Te neutrinoless double beta decay:

$$T_{1/2}^{0\nu}\left(^{130}Te\right) > 2.8\times10^{24}\,y\,,\quad 90\,\%\,CL$$

  - ^{130}Te double beta decay to the first excited state 0^+ of ^{130}Xe:

$$T_{1/2}^{0\nu}\left(^{130}Te \rightarrow {}^{130}Xe^{*}\right) > 9.4\times10^{23}\,y\,,\quad 90\,\%\,CL$$

$$T_{1/2}^{2\nu}\left(^{130}Te \rightarrow {}^{130}Xe^{*}\right) > 1.3\times10^{23}\,y\,,\quad 90\,\%\,CL$$

  - ^{120}Te β^+/EC double beta decay:

$$T_{1/2}^{0\nu}\left(^{120}Te\right) > 1.9\times10^{21}\,y\,,\quad 90\,\%\,CL$$

$$T_{1/2}^{2\nu}\left(^{120}Te\right) > 0.9\times10^{20}\,y\,,\quad 90\,\%\,CL$$

- The muon-induced background was negligible
- The implementation of a low energy threshold trigger opens the possibility to perform dark matter searches in CUORE-0 and CUORE